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COIL ARRAY FOR MAGNETIC RESONANCE IMAGING

This invention relates to a coil arrangement for resonance systems. In particular, the invention is directed to a phased array coil structure, suitable for use in magnetic resonance imaging, which provides improved sensitivity closer to the centre of the object undergoing imaging.

BACKGROUND TO THE INVENTION

In magnetic resonance imaging (MRI) applications, a patient is placed in a strong and homogeneous static magnetic field, causing the otherwise randomly oriented magnetic moments of the protons, in water molecules within the body, to precess around the direction of the applied field. The part of the body in the homogeneous region of the magnet is then irradiated with radio-frequency (RF) energy, causing some of the protons to change their spin orientation. This has the effect of nutating the net magnetization, which was directed with the static magnetic field prior to RF application, and thereby causing a component of the magnetization to be transverse to the applied static field. This precessing magnetization induces measurable signal in a receiver coil tuned to the frequency of precession (The Larmor frequency). This is the magnetic resonance (MR) signal. The useful RF components are those generated in a plane at 90 degrees to the direction of the static magnetic field.

The same coil structure that generates the RF field can be used to receive the MR signal or a separate receiver coil place close to the patient may be used. In either case the coils are tuned to the Larmor precessional frequency ω_0 where $\omega_0 = \gamma B_0$ and γ is the gyromagnetic ratio for a specific nuclide and B_0 is the applied static magnetic field.

Conventionally, when imaging the thorax, a whole body radio frequency coil is used in both transmit and receive modes to enable full coverage of the anatomy. By distinction, when imaging the head, neck, knee or other extremity, local coils are often used as receivers in conjunction with whole-body transmitter coils. Placing the local coil close to the imaged region improves the signal-to-noise ratio and therefore the spatial resolution as well

as limiting the field of view. In some procedures, local coils are used for both transmission and reception.

In some cases, a plurality of RF receiver coils forming an NMR phased array are used to enable MR signals from multiple regions in the body to be acquired at the same time (see for example US patent no. 4,825,162). In this manner parallel imaging methods may be used to advantage in tailoring the region of interest and/or reducing scan times for comparable resolution to single receiver systems. Popular parallel imaging methods include "SMASH" (DK Sodikson and WF Manning, "Simultaneoaus acquisition of spatial harmonics (SMASH): fast imaging with radiofrequency arrays," Magn. Reson. Med. 38:591-603, 1997) and "SENSE" (KP Pruessmann, M. Weigner, MB Scheidegger and P. Boesinger, "SENSE: sensitivity encoding for fast MRI," Magn. Reson. Med. 42; 952-962, 1999).

In prior art phased array coils, the multiple receiver coils are arranged linearly in a plane, or can be wrapped circumferentially around a cylinder or similar shape. They are wrapped in a serial fashion, that is one coil after the other. The coils are placed either overlapping or adjacent to each other to eliminate their coupling. (See for example, JR Porter, SM Wright and A Reykowski, "16-element phased array head coil," Magn. Reson. Med. 40: 272-279, 1998).

While these coils have been effective in producing complete images of an anatomical region, such as the brain, by combining signals from each of the array elements, it is a characteristic of all such prior art coil arrangements that the point of maximum sensitivity of each element is superficial to the anatomy under study. Often the area of diagnostic interest, in the head, for example, may be located away from the surface, deeper in the brain.

It is an object of the invention to provide an improved coil array in which each coil element has its maximum sensitivity close to the centre of the object under study.

It is a further object of the invention to provide a rotary switched phased array radio frequency structure.

BRIEF SUMMARY OF THE INVENTION

In one broad form, the invention provides a radio frequency (RF) coil array for use in resonance imaging and/or analysis of a subject located within a space in which a magnetic field is operatively applied in a first direction, the coil array comprising a plurality of coil elements angled relative to each other and electrically separate from each other, each coil element having a pair of main conductors extending generally parallel to the direction of the magnetic field and located on opposite sides of the space, and a pair of connection conductors connected between respective ends of the main conductors.

The main conductors normally carry equal currents but in opposite directions.

Typically, the space is a cylindrical space and the main conductors extend axially and are located diametrically opposite each other. The coil elements are therefore located in respective diametrical planes of a cylinder, and spaced angularly around the axis of the cylinder. Preferably, the elements are spaced equally.

Each coil element has its maximum sensitivity close to the centre of the object under study.

For practical purposes, the connection conductors at one or both ends of the coil element may be positioned around the circumference of the cylinder to provide access to within the cylinder. The coil elements can be wound from a length of wire in a suitable manner.

In one embodiment of the invention, each element is a receiver coil individually connected to a pre-amplifier and receiver channel, and actively decoupled from a larger volume transmitter coil. Signals from each of the elements are later combined to form a composite image.

In another embodiment of the invention, each element is used for both transmission of RF energy and reception of the magnetic resonance signal.

In a still further embodiment, selected elements may be used for transmission and different elements for reception, the selection of said transmission and reception elements may change desirably during an imaging

sequence. For example, the coil elements can be arranged in one or more orthogonal pairs, one coil element in each pair being adapted for use as a transmitter coil and the other coil element in each pair being adapted for use as a receiver coil. As the coils are orthogonal, there is negligible coupling between them. Each orthogonal coil pair is sequentially activated. A receiver channel is switched to the receiver coil of the active orthogonal pair.

Such rotary switched phased array structures may be used to advantage in routine imaging sequences or with imaging sequences that sample the imaging region using rotary "k-space" techniques, such as back-projection or Propeller (J.G. Pipe, "Turboprop - an improved Propeller Sequence for Diffusion Weighted MRI" *Proc. Intl. Soc. Magn. Reson. Med.* **10**, 435 (2002)) sequences and, in these circumstances, are particularly advantageous for the imaging of short T_2 relaxation constant materials.

In order that the invention may be more fully understood and put into practice, preferred embodiments thereof will now be described, by way of example only, with reference to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a prior art "birdcage" coil array in cylindrical form.

FIG. 2 shows the sensitivity profile of a single prior art array element, with the circular coil centre being located at X=Y=0.

FIG. 3 is a schematic diagram illustrating a two element coil array, according to one embodiment of the invention.

FIG. 4 is a schematic diagram illustrating a four element coil array, according to another embodiment of the invention.

FIG. 5 is a schematic diagram illustrating the general connectivity of the coil array of Fig 3 when used for parallel imaging.

FIG. 6 is a schematic diagram illustrating a coil array with complete cylindrical access.

FIG. 7 is a series of images of a silicon oil cylindrical phantom, acquired using a prototype rotary array coil. The image at the top left is the sum-of-squares image combination of the images from the 4 elements (depicted in the other images).

FIG 8 is a schematic diagram of another embodiment of the coil array illustrating a capacitor arrangement which assists with element isolation.

FIGS 9A to 9D show S11 curves for the respective coil elements in the array of FIG 8 when all other coil elements were simultaneously tuned.

DETAILED DESCRIPTION OF THE INVENTION

Fig 1 shows a prior art MRI phased array general coil layout, in which the coil elements are placed adjacent or partially overlapping around the outside of a cylinder (not shown) or similarly shaped former. That is, the coil elements are located on the circumferential surface of a cylinder. As is routine in the prior art, a single large resonator, external to the array transmits radiofrequency energy to a patient undergoing an MRI scan within the array. Each element of the array acts as a receiver coil, and all coils generally receive signal simultaneous, thereby enabling parallel acquisition of signals from regions within the cylinder.

As is known in the art (see for example, P. Roemer, W.A. Edelstein, C.E. Hayes, S.P. Souza and O.M. Mueller, "The NMR Phased Array," *Magn. Reson. Med.* **16**, 192-225 (1990)), the interaction between the coils may be reduced by overlapping the coils in a prescribed manner, connecting low-impedance pre-amplifiers to each coil and/or having a common conductor containing a predefined capacitor; or a combination of these three methods. A typical sensitivity profile of a single element of the prior art coil array is shown in Figure 2, where it is clear that the region of high sensitivity is close to the plane of the coil and falls away rapidly away from the coil plane.

In contradistinction, in the present invention, each of the elements of the coil array forms a circuit which has a plane of maximum sensitivity that generally contains the axis of the cylinder. That is, the plane of each element cuts radially or diametrically through the cylinder rather than wrapping circumferentially around it, as in the prior art. This is advantageous in that the region of maximum sensitivity is central rather than peripheral to the object being imaged. This is often preferable in a diagnostic sense.

FIG. 3 illustrates conceptually or schematically, the orientation of a 2-element rotary or angular array according to one embodiment of the

invention. In an N-element array, each coil element is rotated or angled from the nearest element by 180/(N) degrees, i.e. they are spaced equi-angularly around the cylinder. For example, elements 10 and 11 are separated by 90 degrees.

FIG. 4 shows an example of a 4-element array, in which each of the coil elements 10,11,12 and 13 are separated from the nearest element by 45 degrees. It is to be understood that the invention also encompasses the use of unequal angular spacing of the elements.

Each of the elements of the array are tuned to the appropriate Larmor precessional frequency and, in a preferred embodiment, are connected to separate preamplifiers and receiver channels, so that each of the elements can acquire signal simultaneously, as is illustrated in the schematic block diagram of FIG. 5.

In another embodiment of the invention, one of the coil elements of the array acts as a transmitter element and all others as receiver elements. Alternately, each of the elements may act as both transmitter and receiver.

In a further embodiment, a selected pair of orthogonal coil elements (elements 10 and 12 in FIG 4, for example) act as a transmitter receiver pair, where one element transmits, say element 10 and the other (element 12) receives, with all other elements inactive. Then, sequentially, the next rotary orthogonal pair act as transmitter/receiver (elements 11 and 13) and so on through the set of N elements. The receiver channel is sequentially switched to the particular active receiver coil element.

When employed as transmitter coils, each element can be driven with a different amplitude and phased radiofrequency pulse, so as, for example, to generate circularly polarized transmission radiofrequency fields. Such tailoring of radio frequency drives is also useful in high frequency applications to correct for the propagation distortions caused by the dielectric and conductive nature of human tissue. By appropriately driving the rotary elements these non-symmetric effects can be largely compensated, resulting in images that give a more accurate representation of the patient's anatomy.

The rotary progression or acquisition in this manner can be closely linked to MRI imaging techniques. In these sequences, the way in

which the imaging gradients are used to scan the imaging region is angular or rotary rather than rectilinear in so-called "k-space" (see, for example, P.T. Callaghan, Principles of Magnetic Resonance Microscopy, Oxford University Press, 1994). Such imaging methods that sample imaging space in a rotary manner include back-projection imaging methods, "propeller" sequences and some variants of spiral imaging (C.H. Meyer, B.S. Hu, D.G. Nishimura, A. Macovski, "Fast Spiral Coronary Artery Imaging" *Magn. Reson. Med.* **28**, 202-213, 1992).

While not limited to use with these sequences, the rotary phased array is advantageous in speeding up these types of imaging protocols.

While FIGS 3-5 illustrate the general principles of the rotary array of this invention, the coil structures need to allow patient access to be useful in practice. The conductors of each element parallel with the z-axis and positioned on the periphery of the cylinder are called the main conductors of each coil element, and the other two conductors which connect these main conductors and complete the coil element are called connection conductors. The connection conductors of each coil element at one or both of the ends of the structure (i.e., the planes orthogonal to the z-axis at the furtherest extents of the array being the top and bottom ends), are placed around the circumference of the cylinder. This allows complete access at one or both ends and is, for example, a structure useful for head imaging.

FIG. 6 illustrates schematically a structure in which the connection conductors of all coil elements are positioned around the circumference of the cylinder at both the top and bottom ends of the array, thus allowing complete cylindrical access to the patient. In this example, switch points A and B may be alternately connected to points 2 & 4 then 1 & 3, or each of the elements may be permanently connected to respective separate pre-amplifiers and receiver channels as shown schematically in FIG. 5.

Positioning the connection conductors around the periphery should not affect the field unduly. The transverse field is the useful RF field for MRI applications, and since this is generated primarily by conductors running parallel to the main axis (i.e., the main conductors), the strongest field is in the

middle of the cylinder if the main conductors are diametrically opposite each other on the periphery of the cylinder.

Typically in prior art elements, any overlap between adjacent coils is small - just enough to minimize mutual inductance. In the prior art, when there are just 2 elements, they are wrapped around the periphery. So the main conductors of one element are close or adjacent to the main conductors in the other element. In the invention, they would still be 90 degrees apart. Furthermore, as the number of elements increases, in prior art coils the maximum sensitivity moves closer to the periphery of the cylinder. On the other hand, with the coil arrangement of the invention, as the number of elements increases, maximum sensitivity remains near the centre of the cylinder.

To demonstrate a preferred embodiment of the present invention, a 4-element transmit/receive rotary array was constructed around a cylinder of diameter 64mm and length 110mm. Each element was tuned and matched to operate simultaneously at 85 MHz (corresponding to ^{1}H Magnetic Resonances at 2 Tesla field strength) and decoupled from each other.

FIG 7 shows the transmit/receive images from each of the 4 rotary elements in turn, and a sum-of-squares combined image (at the top right) which demonstrates a high uniformity of signal across the imaging region, particularly in the central region as desired.

FIG. 8 illustrates an embodiment of the invention in which the elements are used for simultaneous parallel acquisition, the placement of the capacitors and the nature of interconnections assisting with element isolation which is an important consideration for multi-element arrays.

FIGS 9A to 9D demonstrate the isolation between coil elements of FIG 8. In this example, all coil elements were tuned to the same resonant frequency and were inductively excited as indicated by the arrows on the left of each figure. The S11 curves on the right of the respective figures indicate that in all cases the elements are very well isolated and unaffected by the proximity of the other tuned elements. If substantive coupling were evident, the S11 curves would not be of the shape indicated but would have a dual

minima or a 'splitting' of the curve. Such splitting is known to those skilled in the art to indicate substantive coupling.

The foregoing embodiments are illustrative only of the principles of the invention, and various modifications and changes will readily occur to those skilled in the art. The invention is capable of being practiced and carried out in various ways and in other embodiments. It is also to be understood that the terminology employed herein is for the purpose of description and should not be regarded as limiting.

As such, those skilled in the art will appreciate that the invention is not limited to the exact constructions and operation shown and described, but includes all suitable modifications and equivalents within the scope of the claims which are to be regarded as including such equivalent constructions insofar as they do not depart from the spirit and concept of the invention.